QUINTESSENCE AND THE DARK MATTER ABUNDANCE

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Abstract.   Results of a recent study [1] on how the Quintessence scalar could affect the relic abundance of dark matter particles are presented.

1   Introduction

The standard cosmological scenario assumes that before Big Bang Nucleosynthesis (BBN), the universe was dominated by radiation with the Hubble parameter evolving like $H^2 \sim \rho_r \sim a^{-4}$, where ρ_r is the energy density of radiation and a is the scale factor of the universe. However, if we imagine to add a significant fraction of scalar energy density ρ_ϕ to the background radiation at some time in the past, and if $w_\phi > w_r = 1/3$, then ρ_ϕ would decay more rapidly than ρ_r, but temporarily increase the global expansion rate. A measurable effect of this modification to the standard scenario is the anticipation of the 'freeze-out' time of neutralinos and the consequent enhancement of their relic abundance, as explicitly calculated in [2].

In a flat universe, a scalar field with potential $V(\phi)$ obeys the equations

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0 \; ; \quad H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_p^2} \, \rho \; . \tag{1}$$

For any given time during the cosmological evolution, the relative importance of the scalar energy density w.r.t. to matter and radiation in the total energy density $\rho \equiv \rho_m + \rho_r + \rho_\phi$ depends on the initial conditions, and is constrained by the available cosmological data on the expansion rate and large scale structure. If the potential $V(\phi)$ is of the runaway type, the initial stage of the scalar evolution is typically characterized by a period of so–called 'kination' [3] during which the scalar energy density $\rho_\phi \equiv \dot{\phi}^2/2 + V(\phi)$ is dominated by the kinetic contribution $E_k = \dot{\phi}^2/2 \gg V(\phi)$, giving $w_\phi = 1$. After this initial phase, the field comes to a stop and remains nearly constant for some time ('freezing' phase), until it eventually reaches an attractor solution [3].

Then, if we modify the standard picture according to which only radiation plays a role in the post-inflationary era and suppose that at some time $\hat{t}$ the scalar contribution was small but non negligible w.r.t. radiation, then at that time the expansion rate $H(\hat{t})$ should be correspondingly modified. During the kination phase the scalar to radiation energy density ratio evolves like $\rho_\phi/\rho_r \sim a^{-3(w_\phi - w_r)} = a^{-2}$, and so the scalar contribution would rapidly fall off and leave room to radiation. In this way, we can respect the BBN bounds and at the same time keep a significant scalar contribution to the total energy density just few red-shifts before[1]. The increase in the expansion rate H due to the additional scalar contribution would anticipate the decoupling of particle species and result in a net increase of the corresponding relic densities. As shown in [2], a scalar to radiation energy density ratio $\rho_\phi/\rho_r \simeq 0.01$ at BBN would give an enhancement of the neutralino codensity of roughly three orders of magnitude.

2   The model

The enhancement of the relic density of neutralinos requires that at some early time the scalar energy density was dominating the Universe. This fact raises a problem if we want to identify the scalar contribution responsible for this phenomenon with the Quintessence field [1]. Indeed, the initial conditions must be such that the scalar energy density is sub-dominant at the beginning, if we want

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[1]For example, a scalar to radiation ratio $\rho_\phi/\rho_r = 0.01$ at BBN ($z \simeq 10^9$) would imply $\rho_\phi/\rho_r = 0.1$ at $z \simeq 3.16 \times 10^9$ and $\rho_\phi/\rho_r = 1$ at $z \simeq 10^{10}$, if the scalar field is undergoing a kination phase.

the Quintessence field to reach the cosmological attractor in time to be responsible for the presently observed acceleration of the expansion [3]. For initial conditions $\rho_\phi \gtrsim \rho_r$ we obtain instead an 'overshooting' behaviour: the scalar field rapidly rolls down the potential and after the kination stage remains frozen at an energy density much smaller than the critical one. However, as shown in [4], more complicated dynamics are possible if we relax the hypothesis of considering a single uncoupled scalar. The presence of several scalars and/or of a small coupling with the dark matter fields could modify the dynamics in such a way that the attractor is reached in time even if we started, for example, in the overshooting region.

More fields. Consider a potential of the form $V(\phi_1, \phi_2) = M^{n+4} (\phi_1\phi_2)^{-n/2}$, with M a constant of dimension mass. In this case, as discussed first in [4], the two fields' dynamics enlarges the range of possible initial conditions for obtaining a quintessential behaviour today. This is due to the fact that the presence of more scalars allows to play with the initial conditions in the fields' values, while maintaining the total initial scalar energy density fixed. Doing so, it is possible to obtain a situation in which for a fixed ρ_ϕ^{in} in the overshooting region, if we keep initially $\phi_1 = \phi_2$ we actually produce an overshooting behaviour, while if we choose to start with $\phi_1 \neq \phi_2$ (and *the same* ρ_ϕ^{in}) it is possible to reach the attractor in time. This different behaviour emerges from the fact that, if at the beginning $\phi_2 \ll \phi_1$ then, in the example at hand, $\partial V/\partial\phi_2 \gg \partial V/\partial\phi_1$ and so ϕ_2 (the smaller field) will run away more rapidly and tend to overshoot the attractor, while ϕ_1 (the larger field) will move more slowly, join the attractor trajectory well before the present epoch and drive the total scalar energy density towards the required value.

Interaction. Suppose now that the Quintessence scalar is not completely decoupled from the rest of the Universe. Among the possible interactions, two interesting cases are the following:

$$V_b = \frac{b}{2} H^2 \phi^2 \quad \text{or} \quad V_c = c\rho_m\phi \tag{2}$$

If we add V_b or V_c to $V = M^{n+4}\phi^{-n}$, the potential will acquire a (time-dependent) minimum and the scalar field will be prevented from running freely to infinity. In this way, the long freezing phase that characterises the evolution of a scalar field with initial conditions in the overshooting region can be avoided. Effective interaction terms like V_b in eq. (2) are discussed in Refs. [5], where it is shown that supersymmetry breaking effects in the early universe can induce mass corrections to the scalar Lagrangian of order H^2. The second type of interaction (V_c in eq. (2)) can emerge in the context of scalar-tensor theories of gravity (see, for example Ref. [6]), in which a metric coupling exists between matter fields and massless scalars. The scalar field equation in this context is modified by the presence of an additional source term

$$\ddot{\phi} + 3H\dot{\phi} + \frac{1}{2}\frac{dV}{d\phi} = -4\pi G\alpha(\phi)T \tag{3}$$

where $\alpha(\phi)$ is a generic function of ϕ and T is the trace of the matter energy-momentum tensor $T^{\mu\nu}$. The case $\alpha(\phi) = 0$ corresponds to a scalar field decoupled from the rest of the world.

A more detailed discussion, together with numerical examples, can be found in Ref. [1].

References

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